Energy Economics 74 (2018) 708–720

Contents lists available at ScienceDirect

Energy Economics

journal homepage: www.elsevier.com/locate/eneeco

Green growth planning: A multi-factor energy input-output analysis of the Canadian economy

Mehdi Bagheri [a,*], Zeus Guevara [b], Mohammad Alikarami [c], Christopher A. Kennedy [a], Ganesh Doluweera [d]

[a] Department of Civil Engineering, University of Victoria, Victoria V8W 2Y2, British Columbia, Canada
[b] School of Government and Public Transformation, Instituto Tecnológico y de Estudios Superiores de Monterrey, Mexico City 01389, Mexico
[c] Department of Chemistry, University of Victoria, Victoria V8W 2Y2, British Columbia, Canada
[d] Canadian Energy Research Institute, Calgary T2L 2A6, Alberta, Canada

ARTICLE INFO

Article history:
Received 6 December 2017
Received in revised form 13 July 2018
Accepted 19 July 2018
Available online 24 July 2018

JEL classification:
O2
O5
O38
O11
O21
P18

Keywords:
Green growth planning
Green economy
Canada
Energy input-output analysis
Primary energy
Renewable energy

ABSTRACT

Incorporating socioeconomic and environmental considerations into energy decisions is necessary when tackling climate change and accelerating green growth. In this work, we propose a novel extension of the multi-factor energy input-output model to support evidence-informed energy policy-making and green growth planning through the introduction of eight different multipliers and two green growth indexes. We demonstrate the approach through application at the national scale in Canada. In particular, we quantitatively assess the extent to which changes in final demand impact the domestic and imported primary (and renewable) energy flows, CO_2 emissions, economic expansion, and energy job earnings. The results point to a potential path of green growth in Canada, prioritizing activities that generate economic and job growth at minimal environmental pressure (i.e., fewer CO_2 emissions). Economic activities that are critical for stimulating green growth in the short to medium run are identified, and recommendations are made regarding a longer structural change path for improving the supply chains of other economic activities. This work provides insights to decision-makers seeking strategies (e.g., policy reforms or targeted public expenditure strategies) to accelerate green growth planning on a national scale.

© 2018 Elsevier B.V. All rights reserved.

1. Introduction

"Green Growth" is a term to describe a path of economic growth that utilizes natural resources in a sustainable manner (Abramovay, 2015). Over the past few years, green growth has become an increasingly important paradigm as decision-makers try to advance economic development and environmental protection simultaneously. In particular, governments have been seeking policy reforms, regulatory changes, and targeted public expenditure strategies for accelerating green growth and sustainable development in their jurisdictions (Akbilgic et al., 2015; Dale et al., 2016). Nonetheless, making such decisions is a formidable task due to the complex and dynamic interactions between the economic, energy, and environmental considerations (DeLacy, 2014; Derber, 2015; Schandl et al., 2016).

Energy input-output (EIO) analysis is a widely-recognized approach to investigate the economic, social, and environmental aspects of energy policies, thereby supporting green growth strategy implementation at different levels (Guevara and Domingos, 2017a; Kennedy et al., 2014; Kennedy and Bachmann, 2017; Lang and Kennedy, 2016; Shmelev, 2012; Wolfram and Wiedmann, 2017). Although EIO analysis was initially designed to identify the total amount of energy required for delivering a product/service (i.e., by calculating the direct energy consumed in the production process and the indirect energy requirements embodied in the industry's intermediate inputs), it has also been adopted to study the socioeconomic and environmental impacts of policies (Kennedy and Bachmann, 2017; Liu et al., 2010; Treloar et al., 2001; Wiedmann, 2009).

Over the past two decades, EIO models have been successfully implemented to account the greenhouse gas emissions from energy use within an economy (Kander et al., 2015; Kennedy and Bachmann, 2017; Lenzen et al., 2010; Mohareb and Kennedy, 2014) to study and explore the consequences of policy scenarios on economic activities (Guevara and Domingos, 2017b; Malik et al., 2014; Su and Ang, 2012); and assess the impacts of new technologies on national economics (Lenzen and Dey, 2002; Malik et al., 2014; Wolfram et al., 2016). At

* Corresponding author.
E-mail address: Mbagheri@uvic.ca (M. Bagheri).

https://doi.org/10.1016/j.eneco.2018.07.015
0140-9883/© 2018 Elsevier B.V. All rights reserved.

the international level, EIO analysis has also been applied to investigate the impact of international trades on energy consumption and the environment (Jiang et al., 2015; Su and Ang, 2013; Xia et al., 2015). For example, Jiang et al. (2015) studied the prevalence of foreign-invested enterprises in China's export-related emissions. Unitizing an IO analysis approach, Dietzenbacher et al. (2012) calculated the final demand multipliers to describe the ratio of CO_2 emissions to value added for different energy and non-energy products. Also, there have been studies which use the structural decomposition analysis (SDA) to understand the driving forces behind the embodied emission changes (Su and Ang, 2012; Su and Thomson, 2016).

EIO models are based on the energy and monetary flows within an economy and often classified into two main types: “direct impact coefficient” (direct) and “hybrid-unit” (hybrid) approaches (Miller and Blair, 2009; Raa, 2017). While the direct approach is relatively simple to build and implement, it suffers from lack of consistency due to the discordance with the energy conservation principle unless there are uniform energy prices across economic sectors and final demand categories (Guevara and Rodrigues, 2016; Miller and Blair, 2009). On the other hand, the hybrid-unit approach applies energy units for energy transactions instead of monetary units. Although the hybrid-unit EIO analysis offers a more detailed and practical description of energy flows and is always consistent with the energy conservation principle when compared to the direct method, it still provides a limited understanding of energy flows, i.e., particularly concerning energy conversion and use throughout the economy (Guevara and Domingos, 2017a; Guevara and Rodrigues, 2016; Majeau-Bettez et al., 2016; Rocco, 2016). Meanwhile, there have been few attempts in advancing the capabilities of hybrid EIO methods capabilities (Guevara and Domingos, 2017a, b; Lakshmanan, 2012; Raa, 2017), leading to a better understanding of energy flows within an economy.

Given the fact that the traditional EIO framework does not distinguish trade mode, Duan et al. (2012) and Ma et al. (2015) further present an extended EIO approach which distinguishes Chinese production activity both by trade mode and firm ownership. Utilizing such an extended EIO approach, it becomes viable to analyze the destination of national income flows linked to China's exports (Dietzenbacher et al., 2012; Su et al., 2013). Besides the traditional multipliers, Su and Ang (2017) proposed the aggregate embodied intensity (AEI), defined as the ratio of embodied energy (or emissions) to embodied value added. They also obtained the relationships among AEI indicators at aggregate, final demand and sectoral levels and proposed the multi-SDA to study the AEIs changes at different levels.

Recently, Guevara and Rodrigues (2016) developed a combined method by integrating the fundamental characteristics of both direct and hybrid approaches. Despite this method's success in linking the energy sectors to the rest of the economy, the model application is limited by an assumption that energy sectors are independent with no inputs from non-energy to the energy sectors. Ultimately, Guevara and Domingos (2017a) proposed an innovative EIO modeling framework, i.e., multi-factor energy input-output (MF-EIO), which not only distinguishes the energy conversion and consumption processes in an economic system but also expands the model suitability for energy efficiency accounting. In particular, MF-EIO is capable of characterizing the total energy outputs using energy efficiency indicators, end-use energy characteristics, and non-energy structural features of the economy. In comparison to the standard hybrid-unit approach, MF-EIO analysis offers a more precise and more detailed exposition of energy flows within an economy, thereby facilitating green growth planning and implementation (Guevara and Domingos, 2017a, b; Lenzen, 2016). Despite the great promise of MF-EIO analysis in evaluating energy use and efficiency trends through decomposition calculations (Guevara and Domingos, 2017a, b), it has not yet been applied in a real-scale economy to facilitate low-carbon development planning and analysis.

At the national level, Canada is among the world's top energy users mainly due to a heavy reliance on energy-intensive industries, harsh climate, vast geography, low population density, as well as a high standard of living (Bagheri et al., 2018; OCDE, 2016). Meanwhile, Canada is among the world's most reliable energy producers owning vast and diverse resources such as oil and gas, coal, hydropower, biomass, solar, geothermal, wind, marine and nuclear (Barrington-Leigh and Ouliaris, 2017; World Energy Investment, 2017). Thus, environmentally sustainable use and supply of energy resources are vital to facilitating Canada's economic and employment growth while meeting its emission reduction targets.

Despite the critical role of energy in Canada's economy, there are few studies which utilized EIO analysis to assimilate the complex interactions between energy, economy, social and the environment in the country (Bachmann et al., 2014; Kennedy and Bachmann, 2017). The primary objective of this work is to present and implement a novel extension of the MF-EIO analysis by introducing eight different multipliers, to support green growth planning for Canada. The multipliers are: i) primary energy consumption ii) primary energy production, iii) direct energy demand, iv) total production, v) renewable energy consumption, vi) renewable energy production, vii) CO_2 emissions from primary energy consumption, viii) and energy jobs. This work introduces new green growth indices that can facilitate evidence-informed policy-making and green growth planning in Canada, utilizing the developed multipliers. In this sense, the proposed MF-EIO model can improve the conclusions obtained through current EIO analysis.

The next section describes the multi-factor energy input-output (MF-EIO) analysis by linking: a model of the energy sector in physical units; and a model of the rest of the economy in monetary units. We then introduce the eight MF-EIO multipliers and green growth indices, before using energy flows and financial data from 2013 to provide results for the Canadian economy.

2. Methodology

2.1. Monetary input-output analysis

Under the basic IO framework, the Leontief equation calculates the total output (production) of industries from the sum of sales to other industries and the final demand. L^M is the Leontief (total requirements) matrix, in which *Lij* is indicative of the direct and indirect amount of output by industry *i* required to provide a unit of product of industry *j* to final demand (Miller and Blair, 2009; Raa, 2017). As for the calculation of primary energy use and their respective CO2 emissions, we exclude the energy exports while including the primary energy content of energy imports through the competitive imports assumption. More specifically, while our approach considers the consumption of energy flows for the production or final use within the country, it excludes the (abroad) energy use required for the production of non-energy imports consumed by Canadian industries and final demand. It should be noted that throughout this paper, the superscripts *M* and *E* are indicative of monetary and energy units, respectively.

The product-by-industry approach provides a framework, through the definition of make (V) and use (U) matrices, to extend the fundamental IO analysis to industries that produce more than one product (Miller and Blair, 2009; Raa, 2017). In this context, *Uij* represents the amount of commodity *i* used by industry *j*, and *Vij* represents the amount of commodity j produced by industry *i*. Supposing x_i total outputs of industry *i*, and q_j total outputs of commodity j, the technical coefficient matrix (B) and the commodity-output proportions matrix (D) are calculated by Eqs. (1) and (2):

$$B^M = U^M \left(\widehat{x^M}\right)^{-1} \tag{1}$$

$$D^M = V^M \left(\widehat{q^M}\right)^{-1} \tag{2}$$

where B_{ij} describes some inputs from industry i per unit of output of industry j, and D_{ij} is the share of commodity i that is produced by industry j. Using the make-use framework and Eq. (3), $\dot{L}^M$ (industry-by-product total requirements matrix) transforms final demand by product into total output by industry. Additionally, by supposing industries share the same input structure for all of their products and Eq. (4), $\ddot{L}^M$ (product-by-product total requirements matrix) can be defined to transform final demand by product into total output by product:

$$\dot{L}^M = D^M\left(I - B^M D^M\right)^{-1} \tag{3}$$

$$\ddot{L}^M = \left(I - B^M D^M\right)^{-1} \tag{4}$$

2.2. Multi-factor energy input-output (MF-EIO) analysis

As per the energy flow in the MF-EIO analysis, primary energy corresponds to energy carriers as they are recovered or gathered from the natural environment (i.e., natural resources such as mined coal, collected biomass or crude oil). On the other side, final or secondary energy is the flow of energy carriers that are available for direct use by consumers. A consumer is a unit of the economic system (i.e., industries and households) that requires energy services for production (by industries) or consumption (by households). Subsequently, the primary-to-secondary conversion is the first energy transformation stage in the economy, where primary energy sources are upgraded into more useful forms of energy through conversion processes (Cullen and Allwood, 2010; Guevara and Domingos, 2017a; Haberl, 2006). In addition to the conversion processes, such as oil refining and coal-fuelled electric generation, this conversion stage usually includes other operational processes of the energy sector (e.g., extraction, storage, and distribution) (Bhattacharyya, 2011; Orecchini, 2006; Orecchini and Naso, 2012).

2.2.1. MF-EIO mathematical framework

The targeted economic system consists of energy industries (e.g., oil refineries or wind power generation plants) that deliver energy flows (e.g., crude oil or solar heat), non-energy industries that produce non-energy goods and services, and sectors of final energy and non-energy demand (e.g., residential sector and exports). Table 1(a) represents the structure of the monetary table in monetary units and (b) the corresponding energy table in energy units for the MF-EIO analysis. Given the analogy between energy and monetary transactions presented in Table 1, Eqs. (1) and (2) can be rewritten for energy transactions through Eqs. (5) and (6):

$$B^E = U_e^E\left(\widehat{x^E}\right)^{-1} \tag{5}$$

$$D^E = V^E\left(\widehat{q^E}\right)^{-1} \tag{6}$$

Analogously, similar to Eqs. (3) and (4), the energy Leontief matrices of $\dot{L}^E$ (product-by-product total requirements matrix) and $\ddot{L}^E$ (industry-by-product total requirements matrix) can be defined by Eqs. (7) and (8):

$$\dot{L}^E = \left(I - B^E D^E\right)^{-1} \tag{7}$$

$$\ddot{L}^E = D^E\left(I - B^E D^E\right)^{-1} \tag{8}$$

Based on Table 1, U_{ne}^E represents non-energy industries of the energy table. So, the column sum of U_{ne}^E produce the vector of aggregate direct energy demand (shown by r^E). Thus, C^E is the composition matrix of direct energy demand obtained by Eq. (9):

$$C^E = U_{ne}^E\left(\widehat{r^E}\right)^{-1} \text{ where } r^E = \left(U_{ne}^E\right)' i \tag{9}$$

Subsequently, T^E is the amount of direct energy required by a non-energy industry to produce a unit of economic output for that particular industry (also referred as the direct energy intensity) obtained by Eq. (10):

$$T^E = \widehat{r^E}\left(\widehat{G x^M}\right)^{-1} \tag{10}$$

where x^M is the total industry inputs in the monetary table (Table 1a, excluding monetary flows of energy industries to avoid double-counting), G is a bridge matrix with entries $G_{ij} = 1$ for $i = j$ (indexes of energy industries) and $G_{ij} = 0$ for $i \neq j$. This bridge matrix matches the elements of x^M to their corresponding direct energy demand. In this sense, both monetary and energy elements are kept with the original level of aggregation of their classification systems, while an intensity element is built to perform the necessary aggregations between the two classification systems -as done by Guevara and Rodrigues (2016).

As shown in Table 1a, the monetary table includes both energy and non-energy sectors as well as energy and non-energy products. Thus, it is possible to break down the corresponding technical coefficient matrix into four submatrices:

$$\dot{L}^M = \left[\begin{array}{c|c} L_\alpha & L_\pi \\ \hline L_\beta & L_\varnothing \end{array}\right] \tag{11}$$

where L_α is the submatrix of total energy requirements (including primary and secondary energy) of energy industries per unit of final energy demand; and L_β is the sub-matrix of total non-energy requirements of energy industries per unit of final energy demand. Similarly, L_π is the sub-matrix of total direct energy requirements of non-energy industries per unit of final non-energy demand. Finally, $L_\varnothing$ is the sub-matrix of total non-energy requirements of non-energy industries per unit of final non-energy demand. Based on the MF-EIO framework, the vector of total energy use (primary + secondary) in energy unit (q^E) can be calculated using Eq. (12):

$$q^E = \left(\dot{L}^E\right)\left(C^E\right)\left(T^E\right)(L_\varnothing)\left(f_{ne}^M\right) + \left\{\dot{L}^E + \left(\dot{L}^E\right)\left(C^E\right)\left(T^E\right)(L_\beta)B\right\}\left(f^E\right) \tag{12}$$

where f_{ne}^M is the monetary non-energy final demand (excluding monetary flows of energy industries to final demand to avoid double-counting), f^E is the energy final demand (in energy unit), and B is the average energy prices in the economy. While the first term in Eq. (12) represents the energy use to meet final non-energy demand, the latter term indicates the energy requirements to satisfy final energy demand. Moreover, L_β is relatively small in most cases, which makes the product $(\dot{L}^E)(C^E)(T^E)(L_\beta)B$ negligible (Guevara et al., 2017).

2.3. MF-EIO multipliers

Using the ME-EIO framework, this section calculates eight different multipliers. Multipliers refer to the effects of total economic output, energy use or other socioeconomic and environmental indicators caused by a unitary change in the final demand for a specific product (Liu and Liang, 2017; Richardson, 1985; Szyrmer, 1992). In other words, the multiplier measure μ_j reveals the total requirements (i.e., direct plus indirect) from all sectors to supply a unit worth of sector j's output to final demand.

Table 1
(a) Monetary supply and use structures (b) energy supply and use structures.

a)

		Energy Commodities				Non-energy Commodities			Energy Industries				Non-energy Industries			Final Demand	Total Output
		1	2	...	m	m+1	...	p	1	2	...	n	n+1	...	k		
Energy Commodities	1								U^M_{11}	U^M_{12}	...	U^M_{1n}	$U^M_{1\,n+1}$	...	U^M_{1k}	f^M_1	q^M_1
	2								U^M_{21}	U^M_{22}	...	U^M_{2n}	$U^M_{2\,n+1}$	...	U^M_{2k}	f^M_2	q^M_2
	⋮								⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮
	m								U^M_{m1}	U^M_{m2}	...	U^M_{mn}	$U^M_{m\,n+1}$	...	U^M_{mk}	f^M_m	q^M_m
Non-energy Commodities	m+1																
	⋮								⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮
	p								U^M_{p1}	U^M_{p2}	...	U^M_{pn}	$U^M_{p\,n+1}$	...	U^M_{pk}	f^M_p	q^M_p
Energy Industries	1	V^M_{11}	V^M_{12}	...	V^M_{1m}	$V^M_{1\,m+1}$	...	V^M_{1p}									x^M_1
	2	V^M_{21}	V^M_{22}	...	V^M_{2m}	$V^M_{2\,m+1}$	...	V^M_{2p}									x^M_2
	⋮	⋮	⋮	⋱	⋮	⋮	⋱	⋮									⋮
	n	V^M_{n1}	V^M_{n2}	...	V^M_{nm}	$V^M_{n\,m+1}$	...	V^M_{np}									x^M_n
Non-energy Industries	n+1	$V^M_{n+1\,1}$	$V^M_{n+1\,2}$	...	$V^M_{n+1\,m}$	$V^M_{n+1\,m+1}$	...	$V^M_{n+1\,p}$									x^M_{n+1}
	⋮	⋮	⋮	⋱	⋮	⋮	⋱	⋮									⋮
	k	V^M_{k1}	V^M_{k2}	...	V^M_{km}	$V^M_{k\,m+1}$	...	V^M_{kp}									x^M_k
Value added									VA_1	VA_2	...	VA_n	VA_{n+1}	...	VA_k		
Total input		q^M_1	q^M_2	...	q^M_m	q^M_{m+1}	...	q^M_p	x^M_1	x^M_2	...	x^M_n	x^M_{n+1}	...	x^M_k		

* *superscript (M) represents monetary transactions*

b)

		Energy Commodities				Energy Industries				Non-energy Industries			Final Demand	Total Output
		1	2	...	m′	1	2	...	n′	n′+1	...	k′		
Energy Commodities	1					U^E_{11}	U^E_{12}	...	$U^E_{1n'}$	$U^E_{1\,n'+1}$	...	$U^E_{1k'}$	f^E_1	q^E_1
	2					U^E_{21}	U^E_{22}	...	$U^E_{2n'}$	$U^E_{2\,n'+1}$	...	$U^E_{2k'}$	f^E_2	q^E_2
	⋮					⋮	⋮	⋱	⋮	⋮	⋱	⋮	⋮	⋮
	m′					$U^E_{m'1}$	$U^E_{m'2}$	...	$U^E_{m'n'}$	$U^E_{m'\,n'+1}$	...	$U^E_{m'k'}$	$f^E_{m'}$	$q^E_{m'}$
Energy Industries	1	V^E_{11}	V^E_{12}	...	$V^E_{1m'}$									x^E_1
	2	V^E_{21}	V^E_{22}	...	$V^E_{2m'}$									x^E_2
	⋮	⋮	⋮	⋱	⋮									⋮
	n′	$V^E_{n'1}$	$V^E_{n'2}$	...	$V^E_{n'm'}$									$x^E_{n'}$
Conversion losses						$-w_1$	$-w_2$	...	$-w_n$					
Total input		q^E_1	q^E_2	...	$q^E_{m'}$	x^E_1	x^E_2	...	$x^E_{n'}$					

* *superscript (E) represents energy transactions in energy units*

2.3.1. Total production (monetary unit)

Given the basic input-output model, industry-demand-to-economy-wide-output multipliers are calculated by the column sum of the inverse Leontief matrix. Similarly, TP^e and TP^{ne} are the total energy and non-energy production multipliers in monetary units, calculated by Eqs. (13a) and (13b). The *TP* multiplier indicates the extend of

economic growth (positive/negative) due to a unit change (increase/decrease) in final demand.

$$TP^{e} = iL_{\alpha} + iL_{\beta} \tag{13a}$$

$$TP^{ne} = iL_{\pi} + iL_{\varnothing} \tag{13b}$$

2.3.2. Primary and renewable energy consumption

The vector of total energy use obtained from (q^E) accounts for both primary and secondary energy flows. Thus, it needs to be decomposed into primary and secondary energy use through a bridge vector, i.e., primary energy coefficient (k_p). More specifically, k_p distinguishes primary flows and accounts for the primary equivalent of renewable energy flows and of imported secondary energy flows. Primary energy consumption (PEC) can be calculated using Eq. (14):

$$PEC = k_p\left(\dot{L}^E\right)\left(C^E\right)\left(T^E\right)(L_{\varnothing})\left(f_{ne}^M\right) + k_p\left(\dot{L}^E\right)\left(\overline{f}^E\right) \tag{14}$$

where k_p is the vector of primary energy coefficients, and $\overline{f}^E$ is the domestic final demand calculated by excluding exports from f^E (as these energy flows are consumed elsewhere). In a similar manner, k_r is the renewable energy coefficient that acts as a bridge vector to identify the renewable flows. Thereby, by substituting k_r with k_p in Eqs. (15a–d), the renewable energy consumption can be obtained in a similar manner. The PEC and REC multipliers indicate growths of primary and renewable energy use due to a unitary change in final demand. Considering Eq. (14), the primary PEC^e and renewable REC^e multipliers for final energy demand can be obtained from Eqs. (15a) and (15b), respectively. Identically, the primary PEC^{ne} and renewable REC^{ne}multipliers for final non-energy demand can be calculated using Eqs. (15c) and (15d):

$$\mu\left(PEC^{e}\right) = k_p\left(\dot{L}^E\right) \tag{15a}$$

$$\mu\left(REC^{e}\right) = k_r\left(\dot{L}^E\right) \tag{15b}$$

$$\mu\left(PEC^{ne}\right) = k_p\left(\dot{L}^E\right)\left(C^E\right)\left(T^E\right)(L_{\varnothing}) \tag{15c}$$

$$\mu\left(REC^{ne}\right) = k_r\left(\dot{L}^E\right)\left(C^E\right)\left(T^E\right)(L_{\varnothing}) \tag{15d}$$

2.3.3. Primary and renewable energy production (PEP)

Eq. (16) defines primary energy production (PEP) indicating the share of domestic primary energy sectors in satisfying the primary energy consumption. It should be noted that in Eqs. (16) and (17a–d), $\dot{L}^E$ is the Leontief matrix calculated from the modified energy table by just accounting for the domestic energy production (extracting imports). PEP can also be utilized as an important factor for evaluating the national energy security within an economy. Analogously, by replacing k_r with k_p, renewable energy production (REP) can be obtained from Eq. (16). Correspondingly, the primary and renewable energy production multipliers for final energy demand and final non-energy demand can be calculated using Eqs. (17c) and (17d):

$$PEP = k_p\left(\dot{L}^E\right)\left(C^E\right)\left(T^E\right)(L_{\varnothing})\left(f_{ne}^M\right) + k_p\left(\dot{L}^E\right)\left(\overline{f}^E\right) \tag{16}$$

$$\mu\left(PEP^{e}\right) = k_p\left(\dot{L}^E\right) \tag{17a}$$

$$\mu\left(REP^{e}\right) = k_r\left(\dot{L}^E\right) \tag{17b}$$

$$\mu\left(PEP^{ne}\right) = k_p\left(\dot{L}^E\right)\left(C^E\right)\left(T^E\right)(L_{\varnothing}) \tag{17c}$$

$$\mu\left(REP^{ne}\right) = k_r\left(\dot{L}^E\right)\left(C^E\right)\left(T^E\right)(L_{\varnothing}) \tag{17d}$$

2.3.4. CO_2 emissions from the primary energy consumption

Energy-related emissions are estimated from the total primary energy use in Canada using emission content factors of primary energy flows. The CO_2 emissions of secondary energy flows are excluded to avoid double-counting as these are indirectly accounted for in the CO_2 emissions of primary flows. The total energy-related CO_2 emissions (shown in Eq. (18)) can be obtained by multiplying the vector of emission factors in tCO_2/TJ (k_{CO2}) by Eq. (14):

$$CO_2 = k_{CO2}k_p\left(\dot{L}^E\right)\left(\overline{f}^E\right) + k_{CO2}k_p\left(\dot{L}^E\right)\left(C^E\right)\left(T^E\right)(L_{\varnothing})\left(f_{ne}^M\right) \tag{18}$$

where k_{CO2} is the CO_2 emissions of primary energy flows, and f_{ne}^M is the final demand of non-energy products in monetary unit. CO_2 multipliers measure the total change in CO_2 emissions that are generated in an economy due to a one-unit increase in final demand. In this case, Eq. (19a) calculates the CO_2 multiplier for final energy demand $\mu\left(CO_2^e\right)$, and Eq. (17b) provides the CO_2 multiplier for final non-energy demand $\mu(CO_2^{ne})$.

$$\mu\left(CO_2^{e}\right) = k_{CO2}k_p\left(\dot{L}^E\right) \tag{19a}$$

$$\mu\left(CO_2^{ne}\right) = k_{CO2}k_p\left(\dot{L}^E\right)\left(C^E\right)\left(T^E\right)(L_{\varnothing}) \tag{19b}$$

2.3.5. Direct energy demand

The direct energy demand (DED) corresponds to the energy flows (mainly secondary) used by non-energy industries for their producing process. The direct energy demand multiplier or final non-energy demand can be calculated by Eq. (20).

$$\mu\left(DED^{e}\right) = i\left(T_E\right)\left(L_{\varnothing}\right) \tag{20}$$

2.3.6. Energy jobs

Eq. (21) calculates the total number of energy jobs (E-Jobs) using the job coefficient vector k_j in Jobs/TJ. Subsequently, the energy job multipliers for final energy demand $\mu(E_Jobs^e)$ and non-energy demand $\mu(E_Jobs^{ne})$ can be obtained from Eqs. (22a) and (22b).

$$E_\text{Jobs} = k_j\left(\ddot{L}^E\right)\left(f^E\right) + k_j\left(\ddot{L}^E\right)\left(C^E\right)\left(T^E\right)(L_{\varnothing})\left(f_{ne}^M\right) \tag{21}$$

$$\mu(E_\text{Jobs}^{e}) = k_j\left(\ddot{L}^E\right) \tag{22a}$$

$$\mu(E_\text{Jobs}^{ne}) = k_j\left(\ddot{L}^E\right)\left(C^E\right)\left(T^E\right)(L_{\varnothing}) \tag{22b}$$

The main reason for calculating and incorporating the energy jobs multiplier into this work is the significance of energy jobs for the Canadian economy. Mainly, monitoring energy jobs multiplier will provide planners with a simple proxy to assess the potential impacts of energy decisions on the energy jobs market.

2.4. Green growth indices

In this section, using the MF-EIO multipliers, we proposed two new indices that can be utilized to support green growth development strategies (e.g., policy reforms, regulatory changes, targeted public expenditure strategies).

In achieving this goal, we defined a green economic growth index (i.e., shown by GEGI, Eq. (23a)) that can be utilized as a simple yardstick to assess the extent to which different final non-energy demands

threaten the environment (i.e., through their CO_2 emissions) due to a unit (1 MCAD) of economic expansion.

$$\text{GEGI} = \frac{\mu\,(CO_2)}{\mu\,(TP)} = \frac{\text{CO}_2\text{ emission multiplier [tCO}_2\text{]}}{\text{Total output multiplier [MCAD]}} \tag{23a}$$

Similarly, we defined a green job growth index (i.e., shown by GJGI, Eq. (23b)) that is the ratio of CO_2 emission multiplier to the energy job multiplier (i.e., the numbers of created energy jobs due to 1 terajoules of energy used by final demand). In this regard, the GJGI can be directly translated into the emissions intensity per energy job created from final non-energy and energy demands.

$$\text{GJGI} = \frac{\mu\,(CO_2)}{\mu\,(E_Jobs)} = \frac{\text{CO}_2\text{ emission multiplier [tCO}_2\text{]}}{\text{Total output multiplier [No.of jobs]}} \tag{23b}$$

3. Data preparation

The international energy agency (IEA) statistics and balances of Canada in 2013 were used to construct the energy table. Also, to further disaggregate the energy statistics into the supply and use structure in Table 1b, IEA complementary reports (coal, oil, gas, electricity, and renewable information reports) were utilized. Further, we checked the consistency of the utilized IEA statistics with the national energy data of CANSIM (Canadian socioeconomic database from Statistics Canada, Tables 381-0033 and Table 381-0033) for 2013, and in case of missing data or inconsistencies, the national data were employed. Finally, the input-output tables were assembled and harmonized into a product-by-industry arrangement to calculate the energy-related elements (shown in Table 1b) of the MF-EIO model. The energy-related CO_2 emissions of Canada is estimated through emission factors of primary energy flows from EPA (2015) and EIA (2015). Finally, the energy jobs by technologies were taken from REN21 (2016).

Within the MF-EIO framework, an energy carrier is considered primary only if nature or fuel mining and extraction produced it. The primary energy equivalent for renewable flows and imported secondary energy flows were estimated with the physical content method and with the domestic technology assumption, respectively (UN, 1982; Bhattacharyya, 2011; IEA, 2014). Electricity was further disaggregated (e.g., thermoelectricity, biomass electricity) to reflect the type of resources utilized by generation technologies. As shown in Table 1b, the industries are classified as energy and non-energy industries. Energy industries convert primary into secondary (or final) energies (e.g., oil refineries or wind power generation plants), with the latter predominantly consuming energy carriers to produce other goods/services. Similarly, final demand is categorized into sectors of final energy demand (e.g., residential sector and energy exports) and sectors of final non-energy demand. The built energy table consists of 44 energy carriers, 11 energy industries, and 15 non-energy industries. Lists of primary and secondary energy carries as well as the energy and non-energy industries are presented in Table A1 (Appendix A in the supplementary material).

The data required for constructing the monetary elements of the MF-EIO model were obtained from the Canadian input-output tables at basic prices (CANSIM, 2013). Throughout this paper, the monetary units are presented in a million Canadian dollars (Abbreviated by MCAD). The resulting 2013 input-output table describes the money flows in Canada, consists of 101 non-energy and five energy industries, 219 non-energy and 11 energy products shown in Table A1.

3.1. Energy flows

We present Canada's energy flow Sankey diagram in 2013 (Fig. 1), using the energy supply and use data described above. In Fig. 1, "conversion losses" (also referred to as rejected energy) and "energy services" are calculated based on the energy efficiency of residential (65%), transportation (25%), industrial (80%), and commercial and public services

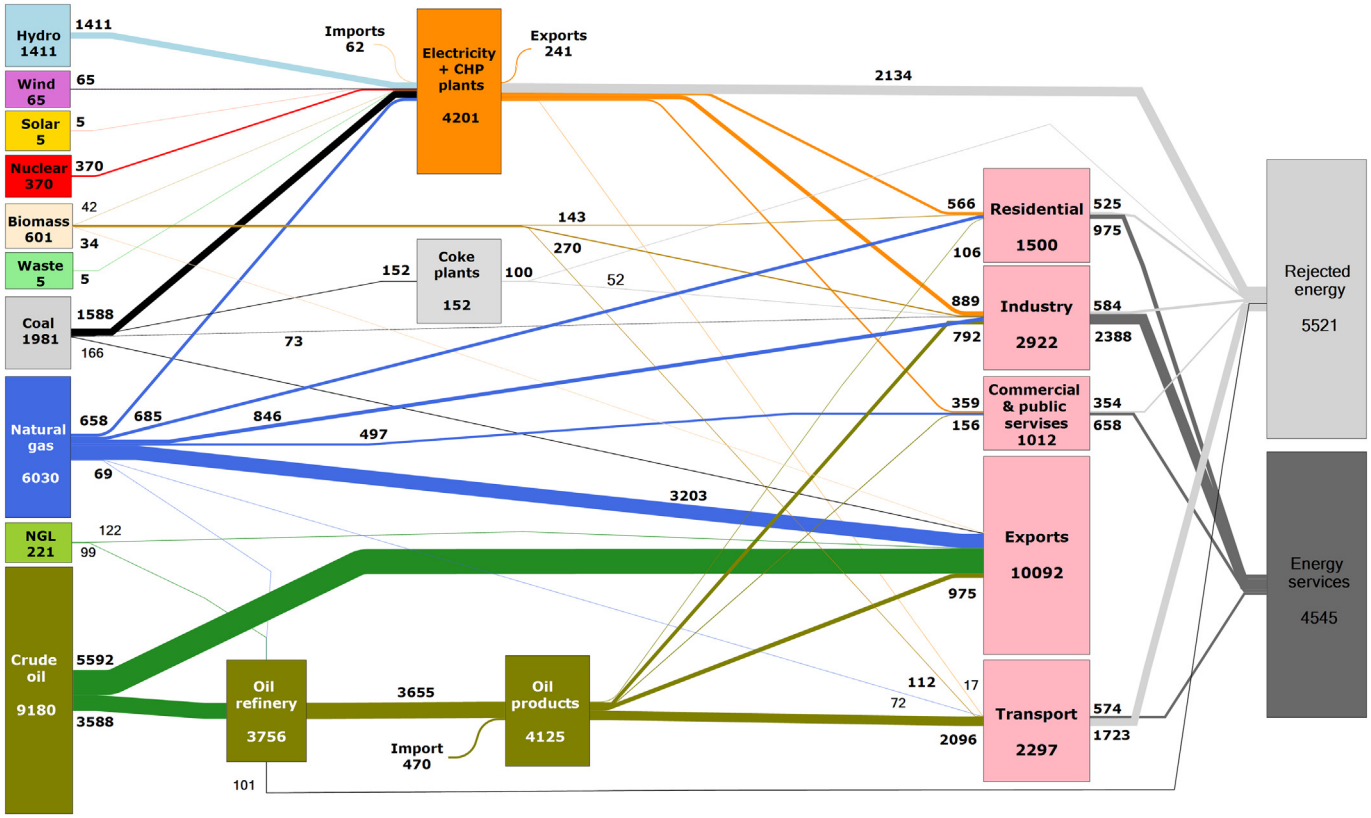

Fig. 1. Canada's energy flow Sankey diagram 2013 (in petajoules).

sectors (65%) (the assumed efficiencies for these sectors, Smith et al., 2011). For example, if supposing sum of inputs to the residential sector is 100 TJ, the values of "energy services" and "conversion losses" would be 65 TJ and 35 TJ, respectively.

According to Fig. 1, Canada's exported energy was almost 34% greater than the total energy consumption of the residential, industry, transport, commercial and public services. Meanwhile, the composition mix of energy exports from Canada is composed of crude oil 55%, natural gas 32%, oil products 10%, coal 1.6% and biomass 1.2%. Other main energy consumers included industry (2922 PJ), transport (2297 PJ) and residential (1500 PJ) sectors, followed by commercial and public services (1012 PJ).

Regarding the use of oil products, the exported portion 974 PJ, plus the consumption by industry 792 PJ, commercial and public services 156 PJ, and residential sectors 106 PJ were almost equal to the transport system with 2096 PJ, reflecting an almost equal share of oil consumption by transportation and the rest of uses (including exports) of oil in Canada. Similarly, commercial and public services with 36% (566 PJ), and the residential sector with 60% (359 PJ) together consumed slightly more electricity as the industrial sector (889 PJ). By comparing the composition of the energy inputs to industry, a similar contribution of electricity, natural gas, and oil products were observed.

Concerning the energy losses, electric and heat plants showed the most significant conversion losses with 2134 PJ, followed by the industry 584 PJ, transportation 574 PJ, and residential 525 PJ. Nonetheless, comparing the composition mix of energy inputs to the electricity and heat plants indicates a slightly higher contribution of coal (~37%) to renewable resources (~38%). Among the renewables, hydroelectric power had the most significant contributions with 92% followed by the wind 4.2%, and biomass 2.8%. Furthermore, natural gas with 16% and nuclear with 9% were among the leading energy suppliers in the electricity and heat plants. Of the energy generated from the electricity and heat plants, the primary use shares belonged to industry and residential sectors with 43% and 27%, followed by commercial and public services 17%, and export 12%. Meanwhile, the share of transportation was just 0.82% of the total energy generated by the electricity and heat plants.

4. Results and discussion

4.1. Energy Leontief matrices

We now illustrate the inter-sectoral energy flows for the production of energy carriers. Tables B1 (Appendix B, supplementary material) is the energy Leontief matrix of $\dot{L}^E$ (product-by-product total requirements matrix, Eq. (7)) which describes the energy production function that also includes primary and secondary carriers only used in the energy sector. For example, based on $\dot{L}^E$ in Table B1, to provide 1 TJ of aviation fuels' final demand, the Canadian economy requires no coke, but it needs an increase of 0.59 TJ of petroleum coke and 0.06 TJ natural gas, and so on. In other words, using $\dot{L}^E$, it is possible to identify the total requirements for producing a unit of any energy product of interest. Unlike the monetary total requirements matrix in which the column sum is equal to one, the column sum for energy total requirement matrix is more than one because of conversion losses (e.g., to heat released to the environment).

We further calculated the total primary energy requirements for producing a unit of any energy product of interest to meet a unit of final energy demand, i.e., by pre-multiplying the diagonal matrix of primary energy coefficients by the total requirement matrix $diag\,(k_p) \times \dot{L}^E$. In this regard, the column sum inverse of $diag\,(k_p) \times \dot{L}^E$ determines the primary to direct energy demand (secondary energy demand by final users and industry) efficiencies. Excluding "Electricity distributed" and "Coke (tar)" with 46% and 41%, the other energy carriers showed a high primary to direct energy demand efficiency of 91–96%.

4.2. Multipliers for energy products

Table 2 presents the MF-EIO multipliers for energy products using a highlighted table format in which darkness/brightness of cells are proportional to their values (e.g., according to the min/max in each column). In other words, for each column the higher the value, the darker the cell. The calculated energy multipliers include PEC (primary energy consumption in TJ/TJ_{fd}), PEP (primary energy production in TJ/TJ_{fd}), CO_2 emissions from the primary energy consumption (in tCO_2/TJ_{fd}), REC (renewable energy consumption in TJ/TJ_{fd}), REP (renewable energy production in TJ/TJ_{fd}), E-Jobs (total energy jobs in $Jobs/TJ_{fd}$). The analysis of multipliers can shed light on the extent to which each final demand could affect the economy and the environment.

Based on Table 2, if coke's final demand (e.g., including Canadian citizens, government, NGOs and capital formation, and export) increases by 1 TJ, the total primary energy consumption in the Canadian economy will increase by 2.422 TJ. Of which, the share of the domestic primary energy increase in satisfying the required primary energy will be 1.716 TJ. In other words, 1 TJ increase in coke's final demand in Canada will rise the Canadian primary energy import by 0.71 TJ. Remarkably, less than 1% of the multiplier effects of coke (tar) corresponded to renewables (i.e., that is indicating the low renewable content in coke's supply chain). Electricity had a domestic multiplier of 1.926 TJ/TJ_{fd} of which almost 1 TJ/TJ_{fd} belonged to primary fossil flows and approximately 48% to renewables, while liquid petroleum gas (LPG) had a 1.037 TJ/TJ_{fd} multiplier with just less than 1% share covered by renewable energy flows.

The highest CO_2 emission multipliers from the primary energy use belong to coke, followed by solid and liquid biofuels. More specifically, the corresponding increase (decrease) in CO_2 emissions due to 1 TJ increase (decrease) in coke's final demand is equal to 208 t. Nonetheless, an increase of 1 TJ in final demand for coke creates 0.034 energy jobs, which is only less than 0.058 for solid and liquid biofuels. As shown in Table 2, in Canada, coke (tar), electricity distributed, gas diesel, lignite and fuel oil are the energy flows with the highest primary energy use multiplier of over 1.10 TJ of additional primary energy use per TJ_{fd} of final demand. This also implies that these flows have the lowest primary-to-final total energy requirements conversion efficiency among other fossil energy flows. Moreover, when comparing different energy products, the final energy demand for liquid petroleum gas (LPG) was met more efficiently with the lowest multiplier of 1.037 TJ/TJ_{fd}.

4.3. Multipliers for non-energy products

Regarding non-energy products, Table 3 presents MF-EIO multipliers for a selected list of non-energy products in a highlighted table format (Table B2 includes the complete lists of non-energy multipliers in supplementary martial). In addition to the energy multipliers, Table 3 includes DED (direct energy demand in TJ/MCAD) and TP (total production in a million CAD). Due to the significance of primary energy consumption in the MF-EIO analysis, non-energy sectors presented in Table B2 are sorted and numbered according to the order of PEC.

Based on Table 3, a MCAD in final demand for water transportation services, wood pulp, and other transportation services (e.g., truck and freight transportation) cause a substantial increase in primary energy use (e.g., water transportation services 28.8 TJ/MCAD, wood pulp 27 TJ/MCAD, truck transportation 26 TJ/MCAD, and freight transpiration 24.1 TJ/MCAD). Among the most energy-intensive non-energy products in the top section of Table 3, wood pulp and printed products supply a significant fraction of their primary energy needs from renewables. In particular, printed products supply over 50% of its primary energy requirement from renewables. Although a 1 MCAD increase in wood pulp's final demand causes a significant increase in Canada's primary energy use, almost 46% of this increase can be met from renewables.

Table 2
MF-EIO multipliers of energy products of Canada (2013).

Energy Products	PEC	PEP	CO2(PE)	REC	REP	E-Jobs
Coke (tar)	2.422	1.716	208	0.009	0.008	0.0343
Electricity distributed	2.167	1.926	98	0.927	0.920	0.0231
Gas diesel	1.104	0.870	74	0.008	0.008	0.0093
Lignite	1.102	1.083	98	0.005	0.005	0.0063
Fuel oil	1.100	0.870	74	0.007	0.008	0.0093
NGL	1.094	1.083	66	0.014	0.005	0.0063
Coking coal (bituminousl)	1.093	1.083	93	0.005	0.005	0.0063
Motor gasoline	1.093	0.870	74	0.007	0.008	0.0093
Sub bit coal	1.093	1.083	97	0.005	0.005	0.0063
Naphtha	1.092	0.870	74	0.007	0.008	0.0093
Natural gas	1.088	1.083	55	0.004	0.005	0.0063
Other kerosene	1.085	0.870	74	0.006	0.008	0.0093
Other products	1.084	0.870	73	0.006	0.008	0.0093
Aviation fuels	1.082	0.870	73	0.006	0.008	0.0093
Petroleum coke	1.072	0.870	73	0.005	0.008	0.0093
Other bituminous & anthra..	1.061	1.083	101	0.003	0.005	0.0063
Solid biofuels	1.039	1.020	107	1.000	1.000	0.0581
Liquid biofuels	1.038	1.020	107	1.017	1.000	0.0581
LPG/Ethane	1.037	0.870	73	0.001	0.008	0.0093

** since all of the column labels are multipliers, the letter μ is not shown on the labels.*

Thus, consumption or exporting more printed products and wood pulp can significantly stimulate the use of renewable energies in the country. Given the larger energy job multipliers for the final demands of the printed products and wood pulp implies the more significant potential of them in the creation of energy jobs in Canada. Other than the various transportation services, we find that chemicals and petrochemicals, ferrous and non-ferrous metal castings and minerals are among the top flows by the primary energy content of the economy.

On the other side, support services and agricultural products have the lowest primary energy requirements with a higher contribution of direct energies in their primary energy flow. For example, physician or dental services (e.g., No. 190 and 191 in Table B2) has a primary energy consumption multiplier of 1.9 TJ/MCAD, of which the contribution of direct energy is almost three-quarters of the primary energy flows. This implies a greater reliance on the secondary energy carries (e.g., electricity) for these sectors with the higher supply chain efficiencies. In other words, the closer the direct energy multiplier is to its correspondent primary energy multiplier, the fewer the losses during the energy supply process. Regarding the domestic primary energy and imported primary energy, urban transit and truck transportation services were among the products with almost 37% dependence on imported primary energy.

Concerning green growth, total production is a particularly important multiplier which shows the extent of economic expansion due to a unitary increase in the final demand (e.g., 1 million CAD dollars). As shown in Table 3, dairy products and animal feed are among the products with the most significant economic expansion. For instance, a million CAD spent on dairy products through final demand will expand the Canadian economy by 2.17 million dollars. Similarly, if the Canadian economy increases wood pulp consumption by one MCAD, the corresponding economic impacts (direct and indirect) is an expansion of 2.09 MCAD.

4.4. Implications for green growth strategies in Canada

Table B3 (in the supplementary material) shows the GEGI values for different final non-energy demands in Canada. According to Table B3, the final non-energy demand of transportation and logistics (including "Transportation services by pipeline", "Truck transportation services", "Urban transit services", "Water transportation services", "Rail transportation services" and "Freight transportation arrangement and customs brokering services") had the largest GEGI values. Two other sectors: "Printed products" and "Converted paper products" also had GEGI values of over 900 tCO_2/MCAD. Comparing the GEGI of 1060 tCO_2/MCAD for No. 6 "Printed products" to 563 tCO_2/MCAD for No.18 "Petrochemicals", we see that a unit of economic expansion by the printed products results in almost 90% more CO_2 emission than a unit of economic expansion by petrochemical sector. Likewise, a unit of economic expansion by No. 44 "metal containers, boilers & tanks" (400 tCO_2/MCAD) will cost the country 100% less CO_2 emissions than an identical economic expansion by No. 13 "Support services for printing & contract printing services for publishers" (800 tCO_2/MCAD).

As shown in Table B4 (Appendix B in the supplementary material), No. 30 "Cement, ready-mixed concrete & concrete products", No. 78 "Glass & glass products including waste & scrap" and No. 66 "Other non-metallic mineral products" have the greatest GJGIs of over 10,000 tCO_2/E-Jobs, reflecting the very high CO_2 emission intensity among all of the different final demands for creating an energy job in Canada. On the other side, final demands such as No. 6 "Printed products", No. 60 "Published products including newspapers, periodicals & books (print & electronic)", No. 2 "Wood pulp", No. 10 "Paper, paperboard & waste", No. 13 "Support services for printing & contract printing services for publishers", and No. 12 "Converted paper products" have the lowest GJGI values of less than 3000 tCO_2/E-Jobs, underlining their low CO_2 emission intensity in creating an energy job.

Table 3
A selected list of MF-EIO multipliers of non-energy products of Canada (2013).

No.	Non-energy Products	PEC	CO2 (PE)	REC	TP	PEP	REP	DED	E-Jobs
1	Water transportation services	28.8	1937	1.67	2.12	18.0	1.08	26.0	0.217
2	Wood pulp	27.0	1853	12.29	2.09	22.6	12.01	20.6	0.623
3	Truck transportation services	26.0	1753	1.49	1.89	16.3	0.96	23.5	0.196
4	Freight transportation arrangement & customs brokering servi..	24.1	1621	1.45	1.78	15.1	0.97	21.7	0.183
5	Urban transit services	22.6	1518	1.36	1.65	14.2	0.91	20.3	0.171
6	Printed products	22.3	1540	11.20	1.45	19.1	10.99	16.7	0.558
7	Rail transportation services	22.0	1485	1.26	1.63	13.8	0.81	19.9	0.166
8	Rail, water, road & other transportation support, maintenance ..	21.7	1456	1.34	1.74	13.7	0.91	19.5	0.165
9	Transportation services by pipeline	21.1	1424	1.20	1.34	13.2	0.77	19.1	0.159
10	Paper, paperboard & waste	20.9	1434	9.52	1.61	17.5	9.31	15.9	0.482
11	Motor vehicle plastic parts	20.6	1260	1.21	1.69	12.7	1.14	17.2	0.128
12	Converted paper products	19.7	1363	9.75	1.32	16.9	9.56	14.8	0.487
13	Support services for printing & contract printing services for pu..	19.7	1352	9.71	1.69	16.8	9.52	14.7	0.483
14	Other bus, taxi & passenger transportation services by road	18.7	1252	1.13	1.42	11.7	0.76	16.8	0.141
15	Plastic & foam building & construction materials	18.6	1140	1.13	1.48	11.5	1.07	15.5	0.117
16	Air transportation services	17.9	1201	1.04	1.44	11.2	0.68	16.1	0.135
17	Support activities for air transportation & aircraft maintenance ..	17.2	1150	1.09	1.57	10.8	0.76	15.4	0.131
18	Petrochemicals	17.2	1049	0.96	1.86	10.6	0.91	14.3	0.105
19	Other plastic products	14.0	858	0.81	1.07	8.6	0.77	11.7	0.087
20	Paints, coatings & adhesive products	13.9	854	1.11	1.17	8.8	1.06	11.5	0.098
100	Prepared & packaged seafood products	3.0	178	0.46	1.14	2.2	0.43	2.4	0.026
101	Religious services	3.0	175	0.67	1.64	2.2	0.64	2.2	0.033
102	Telephone apparatus & other communication equipment	2.9	153	0.56	0.32	2.3	0.54	1.9	0.024
103	Miscellaneous personal & personal care services	2.8	168	0.45	1.48	2.0	0.41	2.2	0.025
104	Sales of other services by Non-Profit Institutions Serving Hous..	2.8	164	0.60	1.68	2.1	0.57	2.1	0.029
105	Ambulatory health care services provided by Non-Profit Institut..	2.8	163	0.59	1.69	2.1	0.56	2.1	0.029
106	Grant-making, civic, & professional & similar organization servi..	2.8	163	0.59	1.69	2.1	0.56	2.1	0.029
107	Labour organization membership services	2.8	163	0.59	1.69	2.1	0.56	2.1	0.029
108	Other services provided by Non-Profit Institutions Serving Hou..	2.8	163	0.59	1.69	2.1	0.56	2.1	0.029
109	Educational services provided by Non-Profit Institutions Servin..	2.8	169	0.72	1.39	2.1	0.69	2.1	0.036
110	Other provincial & territorial government services	2.7	155	0.47	1.83	2.0	0.45	2.1	0.023
206	Deposit intermediation services indirectly measured (FISIM)	1.5	85	0.32	1.35	1.2	0.30	1.1	0.014
207	Banking, credit unions & other depository credit intermediation..	1.5	83	0.31	1.32	1.2	0.30	1.1	0.014
208	Aircraft & aircraft engines	1.5	85	0.29	1.13	1.1	0.27	1.1	0.013
209	Room or unit accommodation services for travellers	1.4	82	0.26	0.89	1.1	0.24	1.1	0.013
210	Licensing of rights to non-financial produced intangible assets ..	1.2	67	0.21	0.62	0.8	0.19	0.9	0.010
211	Imputed rental of owner-occupied dwellings	1.1	57	0.22	1.18	0.8	0.21	0.8	0.009
212	Aircraft parts & other aerospace equipment	0.9	52	0.18	0.71	0.7	0.17	0.6	0.008
213	Computers, computer peripherals & parts	0.8	43	0.16	0.09	0.6	0.16	0.5	0.007
214	Clothing, footwear & accessories	0.8	44	0.14	0.24	0.6	0.14	0.6	0.007
215	Medium & heavy-duty trucks & chassis	0.5	29	0.07	0.23	0.3	0.06	0.4	0.004
216	Audio & video equipment & unrecorded media	0.3	17	0.06	0.03	0.3	0.06	0.2	0.003

** Only some selected non-energy multipliers are presented in Table 3. For the complete lists of them please refer to Table B2 (in supplementary material)*

** * since all of the column labels are multipliers, the letter μ is not shown on the labels.*

As for the energy products, we show GJGI values in Fig. 2. (Note calculation of the GEGI values is not possible due to an inadequate level of disaggregation of energy flows in the monetary input-output data, from which total economic production multipliers are obtainEd.) In Fig. 2, the largest GJGI values belong to "other bituminous & anthracite", "Lignite", "Sub-bituminous coal", and "Coking coal (bituminous)" followed by "Natural gas liquids (NGLs)". In other words, these energy flows showed the highest CO_2 emission intensities per energy job in Canada. Meanwhile, "Natural gas", "Gas-diesel", "Fuel oil", "Motor gasoline", "Naphtha", "Other kerosene", "Other products", "Aviation fuels", "Petroleum coke", and "LPG/Ethane" behaved almost similar in terms of their CO_2 emissions for an energy job creation. Interestingly, among fossil fuels, "Coke (tar)" had the lowest GJGI with less than half emissions per energy job compared to other coal energy carriers such as other bituminous & anthracite", "Lignite", "Sub-bituminous coal", and "Coking coal (bituminous)". On the contrary, solid and liquid biofuels showed the minimum CO_2 emissions for energy job creation. This highlights the critical role of solid and liquid biofuels in boosting energy jobs with minimal environmental impacts (i.e., CO_2 emissions). Given an almost 76.5% share of renewables in the Canadian electricity grid, a relatively low GJGI value of "Electricity distributed" underscores its high potential for creating green energy jobs in the country.

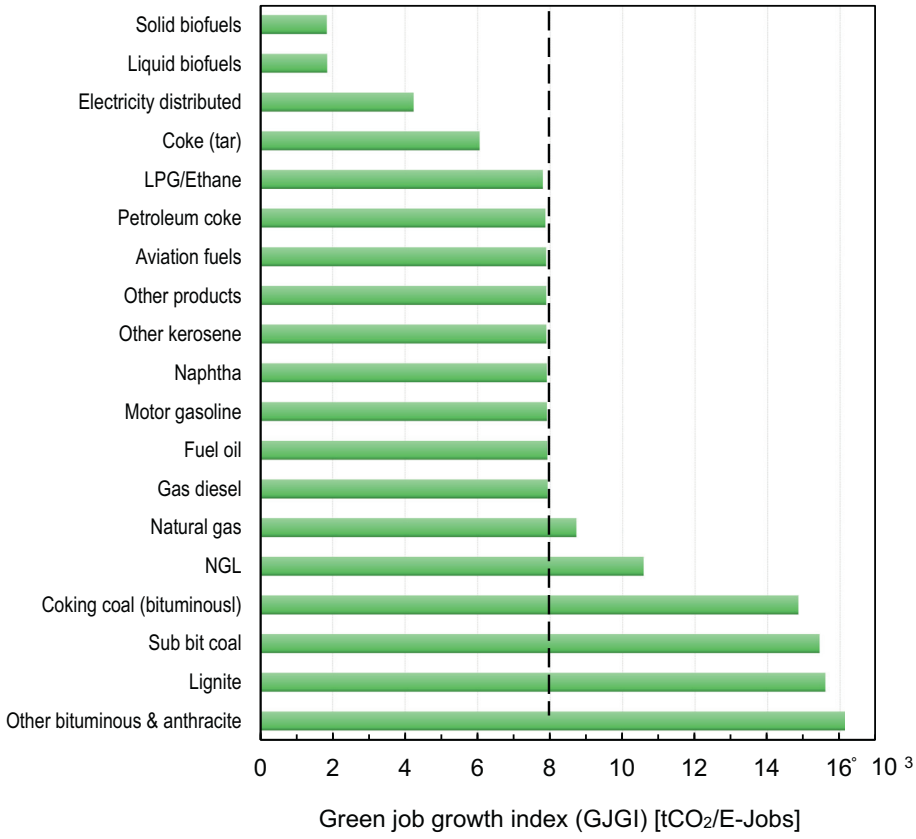

Fig. 2. Green job growth index (GJGI) [tCO_2/E-Jobs] of final energy demand flows.

4.5. Green growth sectors

To simultaneously consider the two green growth indices, Fig. 3 displays the GJGI versus the GEGI. The figure potentially provides planners with a guide to green growth by quantitatively comparing capabilities of non-energy activities to boost the economy and the energy job markets with lowest negative environmental externality (i.e., CO_2 emissions). By dividing the economic sectors into four groups, we distinguish between actions that should be taken in a short run (regions 1&2) and long-run efforts (regions 3&4) to achieving the green growth for Canada. The definition of green indices is based on the concept of energy/emission intensity to quantify the energy/emission requirements for a unit of economic production (e.g., "the lower, the better").

In the green growth context, particular priority and emphasis should be placed on region 1 (shown by green triangular signs). This is because it identifies non-energy flows that currently offer a more significant economic and employment expansion while emitting less carbon dioxide. In other words, the government could be benefited economically, socially and environmentally (less GHG emissions) by increasing/incentivizing final demand on the service side of the economy (e.g., for No. 190 "Rental of residential real estate", No. 211 "Imputed rental of owner-occupied dwellings", No. 109 "Educational services provided by non-profit institutions serving households", No. 121 "Fixed Internet access services", No. 157 "General purpose software", No. 120 "Cable, satellite & other program distribution services", No. 121 "Fixed Internet access services", No. 146 "Fees for the distribution of television & radio program channels", No. 186 "Waste management & remediation services", and so on.) For these cases, the decision-makers should consider supporting final demand increase through taxes, subsidies, government spending, and capital expenditures, particularly in short to medium run (e.g., when the economic structure does not involve a substantial change).

Region 2 (in Fig. 3) entails non-energy flows with a low GEGI but relatively high GJGI values. Some examples include No. 30 "Cement, ready-mixed concrete & concrete products", No. 78 "Glass & glass products including waste & scrap", No. 66 "Other non-metallic mineral products", No. 99 "Transportation engineering construction", No. 98 "Repair construction services", and No. 29 "Warehousing & storage services". When considering the low emission intensities per economic expansion of these sectors, the government may consider increasing the employment potentials although their high GJGI values are less desirable.

Given the low green economic potential of sectors in regions 3 and 4 (Fig. 3), encouraging final demand increase for them is far less appealing. Even though the six flows in region 3 (that are all paper related products/services) can well support the creation of green jobs, their anticipated economic growth is limited and carbon-intensive. Hence, concerning green growth planning in Canada, a longer structural change path is required for the sectors in these regions (3&4), when compared to those in regions 1&2. In particular, for the sectors in regions 3&4, green growth planning should consider improving the supply chains through:

- Improving their energy conversion processes and increasing the share of renewables in their production, e.g., with a particular focus on the non-energy flows with more considerable differences between their PEC and DE multipliers.
- Shifting mix of direct energy consumption in their production industries (e.g., using electric motor vehicles for the transportation purposes, or substitution of coal-fueled with electric or natural gas-fueled heating).
- Mitigating CO_2 emissions from their production processes (e.g., advancing their production technologies, improving energy efficiency and conservation, integrating carbon capturing and sequestration technologies into their producing industries).

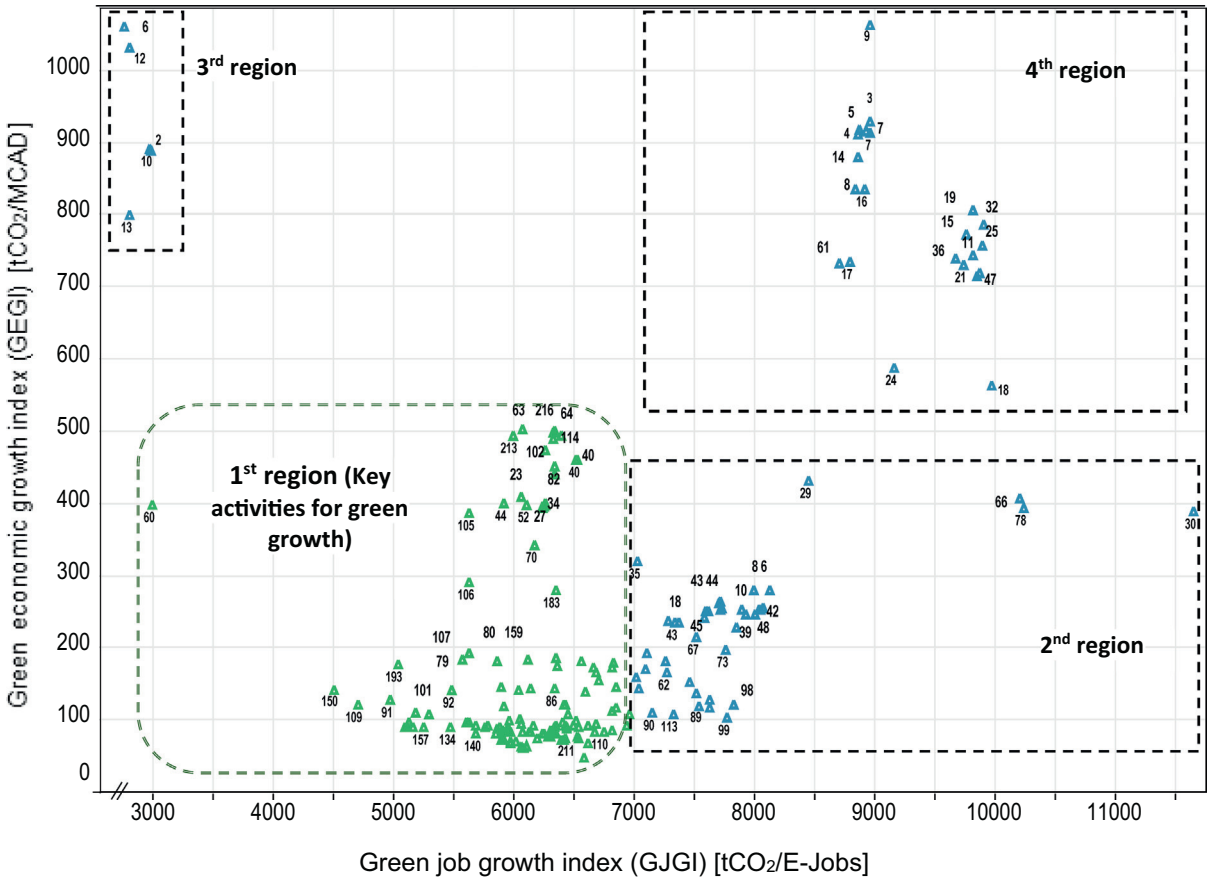

Fig. 3. Canada's green growth decision support map.

- Reducing energy losses associated with the distribution (transportation) of energy carriers (e.g., by decentralizing the energy supply systems and integrating a more energy-efficient energy distribution system).

4.6. Advantages of MF-EIO analysis

Some of the key advantages of the proposed MF-EIO model over the traditional hybrid analysis are summarized as follows:

- The MF-EIO model enables to separate the energy and non-energy conversion effects for the multipliers of non-energy products (e.g., through the difference between the direct and primary energy multipliers). Also, the direct energy multipliers can just be obtained from the MF-EIO approach (i.e., DE multipliers cannot be defined using the hybrid EIO models).
- It provides with a more precise distinction of the primary from the secondary energy carriers which helps to avoid the double counting of emissions and energy use of the secondary energy flows (i.e., that already accounted for the primary flows).
- The MFEIO model in combination with energy balances in physical units can account for non-marketable, non-conventional, by-produced and residual (waste) energy flows that are not included in conventional input-output approaches based on financial data. Therefore, we have a better accounting of total primary energy use and energy-related emissions (while other models usually underestimate energy use and energy-related emissions). For example, while there are only four energy products and industries using the Canadian monetary dataset, the MF-EIO approach allows us to expand the model by 11 industries and 44 energy flows, leading to more disaggregated and detailed multipliers than with other models.
- Moreover, the MF-EIO model allows studying different import assumptions for the energy and non-energy intermediates and final demand under various environmental responsibility frameworks (e.g., excluding the primary energy contents of the non-energy imports while accounting for the primary energy content of final energy imports).

5. Conclusions and recommendations

In this work, we developed a novel extension of energy input-output analysis to facilitate evidence-informed, green growth and energy policy-making through the introduction of eight different final demand multipliers under the multi-factor modeling framework. We also utilized the proposed approach to a model economy (Canada) for green growth planning and implementation at a national scale. By calculating eight multipliers for Canada, we quantified the embodied primary, direct, and renewable energies (domestic and exported), total economic production, as well as energy jobs for over 240 different energy/non-energy sectors within the economy.

Furthermore, by introducing two new green growth indices, we proposed a schematic guideline to assist green growth planning in a short-run (regions 1&2 in Fig. 3) and long-run efforts (regions 3&4 in Fig. 3). More specifically, to support Canada's green growth in a short run, we emphasized increasing final demand for non-energy flows with low CO_2 emission intensity per energy job created and per unit of economic expansion (region 1 in Fig. 3). Moreover, considering the lower green economic potentials for sectors in regions 3 and 4, it is recommended to consider a longer structural change path including more substantial improvements in their energy supply chains, industrial processes, and final demand policies.

Given the little contribution of renewables to supply chains of energy carriers (refer to Fig. 3), the government should support increasing the renewable requirements for final energy demand. In this respect, an efficient approach to growing the renewable energy multipliers would be increasing the share of renewable electricity generation, as electricity is a crucial input to supply chains of other energy carriers. However, having a low overall efficiency of electricity (distributed), Canada should place a particular focus on improving the interconnections of energy sectors for electricity generation and distribution. To further improve energy efficiency of supply chains, government should consider reducing energy losses of energy distribution and transportation (e.g., decentralization of energy supply systems, energy-efficient transportations), upgrading energy conversion technologies, implementing energy recovery solutions (e.g., implementation of waste-to-energy), and switching to less carbon-intensive fuels (e.g., coal-fueled to electric heating). Not only improving the energy efficiency of supply chains will help Canada on tackling climate change, but it will also make the country's production more cost competitive, thereby accelerating the country's transition to a green economy.

Recommendations for future research directions include the investigation of endogenous and cross-over effects between energy jobs, final demand changes and economic expansion (e.g., through social accounting or closed input-output systems). Meanwhile, other works should consider incorporating the total economy-wide jobs into their analysis, evaluating the historical changes and drivers (e.g., structural decomposition analysis), and extending the MF-EIO model for multi-regional analysis.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.eneco.2018.07.015.

References

Abramovay, R., 2015. Beyond the Green Economy. Routledge, London.

Akbilgic, O., Doluweera, G., Mahmoudkhani, M., Bergerson, J., 2015. A meta-analysis of carbon capture and storage technology assessments: understanding the driving factors of variability in cost estimates. Appl. Energy 159, 11–18. https://doi.org/10.1016/j.apenergy.2015.08.056.

Bachmann, C., Roorda, M.J., Kennedy, C., 2014. Developing a multi-scale multi-region input-output model. Econ. Syst. Res. 27 (2), 172–193. https://doi.org/10.1080/09535314.2014.987730.

Bagheri, M., Shirzadi, N., Bazdar, E., Kennedy, C.A., 2018. Optimal planning of hybrid renewable energy infrastructure for urban sustainability: green Vancouver. Renew. Sustain. Energy Rev. https://doi.org/10.1016/j.rser.2018.07.037.

Barrington-Leigh, C., Ouliaris, M., 2017. The renewable energy landscape in Canada: a spatial analysis. Renew. Sust. Energ. Rev. 75, 809–819. https://doi.org/10.1016/j.rser.2016.11.061.

Bhattacharyya, S.C., 2011. Energy Economics: Concepts, Issues, Markets and Governance/Subhes C. Bhattacharyya. Springer, London.

Cullen, J.M., Allwood, J.M., 2010. The efficient use of energy: tracing the global flow of energy from fuel to service. Energy Policy 38 (1), 75–81. https://doi.org/10.1016/j.enpol.2009.08.054.

Dale, G., Mathai, M.V., Oliveira, J.A.P.D., 2016. Green Growth: Ideology, Political Economy and the Alternatives. Zed Books, London.

DeLacy, T., 2014. Green Growth and Travelism: Concept, Policy and Practice for Sustainable Tourism. Routledge, New York.

Derber, C., 2015. Greed to Green: Solving Climate Change and Remaking the Economy/Charles Derber. Routledge, Taylor & Francis, London.

Dietzenbacher, E., Pei, J., Yang, C., 2012. Trade, production fragmentation, and China's carbon dioxide emissions. J. Environ. Econ. Manag. 64, 88–101.

Duan, Y., Yang, C., Zhu, K., Chen, X., 2012. Does the domestic value-added induced by China's exports really belong to China? China World. Econ. 20, 83–102.

EIA, 2015. Monthly Energy Review, February 2015, Energy Information Administration. U.S. Department of Energy, Washington, DC (DOE/EIA-0035(2015/02)).

IEA, 2014. What are the methods of calculation of primary energy equivalent? Available online: https://www.iea.org/statistics/resources/questionnaires/faq/#one, Accessed date: 17 May 2017

Guevara, Z., Domingos, T., 2017a. The multi-factor energy input-output model. Energy Econ. 61, 261–269. https://doi.org/10.1016/j.eneco.2016.11.020.

Guevara, Z., Domingos, T., 2017b. Three-level decoupling of energy use in Portugal 1995–2010. Energy Policy 108, 134–142. https://doi.org/10.1016/j.enpol.2017.05.050.

Guevara, Z., Rodrigues, J.F.D., 2016. Structural transitions and energy use: a decomposition analysis of Portugal 1995–2010. Econ. Syst. Res. 28 (2), 202–223. https://doi.org/10.1080/09535314.2016.1157456.

Guevara, Z., Córdoba, O., García, E., Bouchain, R., 2017. The status and evolution of energy supply and use in Mexico Prior to the 2014 energy reform: an input-output approach. Economies 5 (1), 10. https://doi.org/10.3390/economies5010010.

Haberl, H., 2006. The global socioeconomic energetic metabolism as a sustainability problem. Energy 31 (1), 87–99. https://doi.org/10.1016/j.energy.2004.04.045.

World Energy Investment, 2017. IEA World Energy Investment. OECD Publishing, Paris (Published: 11 July 2017).

Jiang, X., Guan, D., Zhang, J., Zhu, K., Green, C., 2015. Firm ownership, China's export-related emissions, and the responsibility issue. Energy Econ. 51, 466–474.

Kander, A., Jiborn, M., Moran, D.D., Wiedmann, T.O., 2015. National greenhouse-gas accounting for effective climate policy on international trade. Nat. Clim. Chang. 5 (5), 431–435. https://doi.org/10.1038/nclimate2555.

Kennedy, C.A., Bachmann, C., 2017. The energy structure of the Canadian economy. J. Ind. Ecol. 21 (5), 1301–1311. https://doi.org/10.1111/jiec.12493.

Kennedy, C., Stewart, I.D., Ibrahim, N., Facchini, A., Mele, R., 2014. Developing a multi-layered indicator set for urban metabolism studies in megacities. Ecol. Indic. 47, 7–15. https://doi.org/10.1016/j.ecolind.2014.07.039.

Lakshmanan, T.R., 2012. Economic-Environmental-Energy Interactions: Modeling and Policy Analysis. Springer Netherlands.

Lang, T., Kennedy, C., 2016. Assessing the global operational footprint of higher education with environmentally extended global multiregional input-output models. J. Ind. Ecol. 20 (3), 462–471. https://doi.org/10.1111/jiec.12396.

Lenzen, M., 2016. Structural analyses of energy use and carbon emissions – an overview. Econ. Syst. Res. 28 (2), 119–132. https://doi.org/10.1080/09535314.2016.1170991.

Lenzen, M., Dey, C.J., 2002. Economic, energy and greenhouse emissions impacts of some consumer choice, technology and government outlay options. Energy Econ. 24 (4), 377–403. https://doi.org/10.1016/S0140-9883(02)00007-5.

Lenzen, M., Pade, L.-L., Munksgaard, J., 2010. CO 2 Multipliers in Multi-region Input-Output Models. Econ. Syst. Res. 16 (4), 391–412. https://doi.org/10.1080/0953531042000304272.

Liu, L., Liang, Q., 2017. Changes to pollutants and carbon emission multipliers in China 2007–2012: an input-output structural decomposition analysis. J. Environ. Manag. 203, 76–86. https://doi.org/10.1016/j.jenvman.2017.07.061.

Liu, H., Xi, Y., Guo, J.'.E., Li, X., 2010. Energy embodied in the international trade of China: an energy input-output analysis. Energy Policy 38 (8), 3957–3964. https://doi.org/10.1016/j.enpol.2010.03.019.

Ma, H., Wang, Z., Zhu, K., 2015. Domestic content in China's exports and its distribution by firm ownership. J. Comp. Econ. 43 (1), 3–18.

Majeau-Bettez, G., Pauliuk, S., Wood, R., Bouman, E.A., Strømman, A.H., 2016. Balance issues in input-output analysis: a comment on physical inhomogeneity, aggregation bias, and coproduction. Ecol. Econ. 126, 188–197. https://doi.org/10.1016/j.ecolecon.2016.02.017.

Malik, A., Lenzen, M., Ely, R.N., Dietzenbacher, E., 2014. Simulating the impact of new industries on the economy: the case of biorefining in Australia. Ecol. Econ. 107, 84–93. https://doi.org/10.1016/j.ecolecon.2014.07.022.

Miller, R.E., Blair, P.D., 2009. Input-Output Analysis: Foundations and Extensions. Cambridge University Press.

Mohareb, E.A., Kennedy, C.A., 2014. Scenarios of technology adoption towards low-carbon cities. Energy Policy 66, 685–693. https://doi.org/10.1016/j.enpol.2013.10.070.

OCDE, O, 2016. World Energy Statistics 2016. OECD Publishing (1 online resource).

Orecchini, F., 2006. The era of energy vectors. Int. J. Hydrog. Energy 31 (14), 1951–1954.

Orecchini, F., Naso, V., 2012. Energy Systems in the Era of Energy Vectors. Springer London, London.

Raa, T., 2017. Handbook of Input-Output Analysis. Edward Elgar Publishing Limited.

REN21, 2016. Renewables 2016 Global Status Report (Paris: REN21 Secretariat). (2016) (ISBN 978-3-9818107-0-7, Retrieved April 10, 2017).

Richardson, H.W., 1985. Input-output and economic base multipliers: looking backward and forward. J. Reg. Sci. 25 (4), 607–661. https://doi.org/10.1111/j.1467-9787.1985.tb00325.x.

Rocco, M.V., 2016. Primary Exergy Cost of Goods and Services: An Input-output Approach. Springer International Publishing.

Schandl, H., Hatfield-Dodds, S., Wiedmann, T., Geschke, A., Cai, Y., West, J., Newth, D., Baynes, T., Lenzen, M., Owen, A., 2016. Decoupling global environmental pressure and economic growth: scenarios for energy use, materials use and carbon emissions. J. Clean. Prod. 132, 45–56. https://doi.org/10.1016/j.jclepro.2015.06.100.

Shmelev, S.E., 2012. Economic Models and the Environment: Input-output Analysis. Springer, Dordrecht, London, pp. 87–114.

Smith, C.A., Belles, R.D., Simon, A.J., 2011. 2007 Estimated International Energy Flows (No. LLNL-TR-473098). Lawrence Livermore National Laboratory (LLNL), Livermore, CA.

Statistics Canada, 2013. CANSIM (Supply and Use and Input-Output Tables, 2013) (Last updated June 30, 2017).

Su, B., Ang, B.W., 2012. Structural decomposition analysis applied to energy and emissions: some methodological developments. Energy Econ. 34 (1), 177–188. https://doi.org/10.1016/j.eneco.2011.10.009.

Su, B., Ang, B.W., 2013. Input-output analysis of CO2 emissions embodied in trade: competitive versus non-competitive imports. Energy Policy 56, 83–87.

Su, B., Ang, B.W., 2017. Multiplicative structural decomposition analysis of aggregate embodied energy and emission intensities. Energy Econ. 65, 137–147.

Su, B., Thomson, E., 2016. China's carbon emissions embodied in (normal and processing) exports and their driving forces, 2006–2012. Energy Econ. 59, 414–422.

Su, B., Ang, B.W., Low, M., 2013. Input-output analysis of CO2 emissions embodied in trade and the driving forces: processing and normal exports. Ecol. Econ. 88, 119–125.

Szyrmer, J.M., 1992. Input-output coefficients and multipliers from a total flow perspective. Environ. Plan. A 24 (7), 921–937.
Treloar, G.J., Love, P.E.D., Holt, G.D., 2001. Using national input/output data for embodied energy analysis of individual residential buildings. Constr. Manag. Econ. 19 (1), 49–61. https://doi.org/10.1080/014461901452076.
UN, 1982. Concepts and methods in energy statistics with special reference to energy accounts and balances (New York, United Nations).
U.S. Environmental Protection Agency, 2015. Inventory of U.S. Greenhouse Gas. Emissions and Sinks: 1990-2013.
Wiedmann, T., 2009. A first empirical comparison of energy footprints embodied in trade - MRIO versus PLUM. Ecol. Econ. 68 (7), 1975–1990. https://doi.org/10.1016/j.ecolecon.2008.06.023.
Wolfram, P., Wiedmann, T., 2017. Electrifying Australian transport: hybrid life cycle analysis of a transition to electric light-duty vehicles and renewable electricity. Appl. Energy 206, 531–540. https://doi.org/10.1016/j.apenergy.2017.08.219.
Wolfram, P., Wiedmann, T., Diesendorf, M., 2016. Carbon footprint scenarios for renewable electricity in Australia. J. Clean. Prod. 124, 236–245. https://doi.org/10.1016/j.jclepro.2016.02.080.
Xia, Y., Fan, Y., Yang, C., 2015. Assessing the impact of foreign content in China's exports on the carbon outsourcing hypothesis. Appl. Energy 150, 296–307.